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# Projecting future transmission of malaria under climate change scenarios: Challenges and research needs

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## Running title

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*There has been an intense debate about climatic impacts on the transmission of malaria. It is vitally important to accurately project future impacts of climate change on malaria to support effective policy–making and intervention activity concerning malaria control and prevention. This paper critically reviewed the published literature and examined both key findings and methodological issues in projecting future impacts of climate change on malaria transmission. A literature search was conducted using the electronic databases MEDLINE, Web of Science and PubMed. The projected impacts of climate change on malaria transmission were spatially heterogeneous and somewhat inconsistent. The variation in results may be explained by the interaction of climatic factors and malaria transmission cycles, variations in projection frameworks and uncertainties of future socioecological (including climate) changes. Current knowledge gaps are identified, future research directions are proposed and public health implications are assessed. Improving the understanding of the dynamic effects of climate on malaria transmission cycles, the advancement of modelling techniques and the incorporation of uncertainties in future socioecological changes are critical factors for projecting the impact of climate change on malaria transmission.*

**KEY WORDS:** Climate change, malaria, projection, temperature, rainfall, socoecological factors.

# INTRODUCTION

An increase in anthropogenic greenhouse gases (GHGs) in the atmosphere including carbon dioxide ($CO_2$), methane and nitrous oxide has long been identified as a major contributor to global climate change (CC).[1] The Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) reported that global mean surface temperature will likely rise by between 1.1 °C and 6·4 °C by 2100, with best estimates of between 1.8 °C and 4.0 °C.[2] This will increase the level of CC–related risks for the rest of the century.[3] Recent evidence shows that global $CO_2$ emissions may be rising even faster than the most severe projections of the IPCC emission scenarios.[4-7] Due to the high rate of GHG emissions, global mean surface temperature may increase above the current worst–case–scenario, leading to an increasing risk of abrupt and/or irreversible climatic shifts. [3]

One of the major impacts of CC on human health is the possible alteration of dynamic patterns of mosquito–borne diseases (MBDs).[8] Mosquitoes are “cold–blooded” (ectothermic) and thus especially sensitive to climatic changes.[9] Weather influences the survival and reproduction rates of mosquitoes, in turn influencing habitat suitability, distribution, abundance, intensity and annual temporal patterns of mosquito activity (particularly biting rates). It also affects rates of development, survival and reproduction of pathogens within mosquitoes.[10] Malaria is the most thoroughly studied MBD that is largely influenced by climate (e.g. temperature, rainfall) and other socio-ecological factors.[11]

Malaria is caused by eukaryotic protists of the genus *Plasmodium*. It is widespread in tropical and subtropical regions, including much of Sub–Saharan Africa, Asia and the Americas. Five species of *Plasmodium* can be transmitted by mosquitoes to humans (*P. falciparum, P. vivax, P. ovale, P. knowlesi and P. malariae*). The vector responsible for malaria transmission is the mosquito of the genus *Anopheles.* In humans, multiplication of *Plasmodium* parasites within red blood cells causes symptoms that typically include fever and headache, and in severe cases can lead to coma or death. These symptoms usually appear between 10 and 15 days after the number of plasmodium reaches a certain threshold in the blood following the bite of an infective mosquito.[12] The continued existence of malaria in a particular location generally requires a combination of both high human and mosquito population density, along with high rates of transmission between humans and mosquitoes.[13,14]

The life cycle of the malaria parasite is most easily maintained in relatively hot, humid climates. In such areas, there is stable transmission of malaria, with residents found to develop a partial immunity to the disease (beyond the age of five).[12,15] In 2010, nearly all populations at stable transmission risk were located in Africa (80% of the global) or Central, South and East Asia, with a much smaller proportion in the Americas. [15,16] According to the recently updated world malaria distribution map, the temperate or highland regions of Asia (91% of the total population), the Americas (5%) and Africa (4%) experience unstable *falciparum* transmission.[16] In these areas, residents do not develop immunity, are susceptible and therefore suffer more serious illness.[17] Countries in North America, Europe, South Africa, Australia and parts of China no longer experience epidemic or endemic transmission due to factors such as climate, disease control programmes, malaria elimination and eradication. However, sporadic local transmission does occur in some areas, aided by an increasing number of people importing malaria infection from abroad, which in some cases reintroduces the parasite into these regions.[18–20] Many countries are seeing an increasing number of imported malaria cases owing to extensive travel and migration, and more infected people coming from current endemic malaria regions.[21]

According to the WHO malaria report 2012, an estimated 219 million cases of malaria are in 104 countries and territories areas in 2010.[15] Malaria is the 5th cause of death from infectious diseases globally (after respiratory infections, HIV/AIDS, diarrheal diseases, and tuberculosis) and is the 2nd leading cause of death from infectious diseases in Africa, after HIV/AIDS. [22] In 2010, malaria caused an estimated 660,000 deaths, of which 91% were in Africa and 86% were among children under five years of age.[15] Economists believe that malaria is responsible for a loss of up to 1.3% of Gross Domestic Product (GDP) per year in some African countries. In some countries with a heavy malaria burden, the disease may account for as much as 40% of public health expenditure, 30% to 50% of inpatient admissions, and up to 50% of outpatient visits.[23,24] Available funds for malaria control globally are not sufficient to meet need. Thus combining both domestic and international funds, the resources available for malaria control globally were estimated to be US$2.3 billion in 2011,[15] which is US$2.3 billion less than the projected US$5.1 billion needed annually between 2011 and 2020.[17]

The global burden of malaria requires that suitable policies and responses be quickly adopted to reduce or manage the expansion of endemic malaria. The assessment of the potential change in malaria risk caused by CC remains an important, yet controversial topic within the research community.[25] This paper provides a synthesis of projections of the effect of future CC on malaria transmission, and a critical review of the major issues in this field. In addition, current knowledge gaps are identified, and future research directions and implications are proposed.

## METHODS

A literature search was conducted and updated between November 2011 and November 2012, using the electronic databases MEDLINE, Web of Science and PubMed. The key words or Medical Subject Headings (MeSH) terms used were: “climate”, “climate change”, “climate variability”, “global warming”, “greenhouse effect” AND “malaria”, “malaria, cerebral”, “malaria, vivax”, “malaria, falciparum”, AND “project*”, “projecting”, “future” or "scenario*". References and citations of the articles identified were inspected to ensure that the relevant articles were included comprehensively.

Three inclusion criteria were used to select articles for critical analysis. Firstly, articles had to include a projection of future CC–related malaria transmission under climate scenarios. Secondly, only peer–reviewed journal publications in English language were eligible for quality consideration. Finally, only quantitative, empirical studies were included as qualitative studies usually addressed different research questions.

## RESULTS

We identified 426 papers from searches of the selected electronic bibliographic databases. After reviewing the titles of these papers, we retrieved 162 abstracts for detailed evaluation, of which 57 articles were examined in full. Finally, 20 studies met the eligibility criteria and were included in the review. Figure 1 shows a flowchart of this process and reasons for exclusion of articles at each stage. The results were first summarised in tables and then analysed in more detail in the subsequent sections.

[Figure 1 about here]

The results in table 1 show that of the twenty studies, six had a global focus, nine focused on Africa, two on Germany and three on India. The projected period ranged from 2020 to 2100. These studies used different outputs to project the impact of CC on malaria transmission under various CC scenarios. Twelve studies generated local CC from IPCC emission scenarios, while others generated climate or GHGs emission scenarios from local climate models or assumptions (Table 1).These projection models are discussed in further detail in the next section.

[Table 1 about here]

Table 2 shows seven key methodological characteristics that arise in projecting the impact of CC on malaria, including the baseline time period, climate change scenarios considered, climate exposure and other variables considered, spatial and temporal resolution and type of model adopted. The table reveals a range of different methodologies, including the following. 1) Various CC scenarios were applied and the number considered in the individual studies ranged from one to six at the various scales, continent (Africa) and countries. 2) The exposure measures included mean, minimum, median and maximum temperatures which varied from daily to annual timescales. Some studies used multiple temperature indicators.[26–28] 3) Various baseline time periods were chosen, although the most common time period was 1961–1990. 4) In order to project future temperature and rainfall, different studies adopted different versions of climate models derived from various centres or organisations, such as The Hadley Centre Model (HadCM). 5) Both biological and statistical models were used to describe the climate–malaria relationship, in which one or more temperature indicators were included as independent variables. However, few confounders were considered in these models. 6) Future population growth, socioeconomic status, urbanisation, migration and malaria control programs were rarely considered in the models. 7) Some results were based on coarse data from GCMs and others came from regional climate Models (RCMs). Also, some of studies interpolated their results to a much higher resolution.[19, 25, 28–32]

[Table 2 about here]

## The commonalities of the included studies

Notwithstanding the methodological differences, there are commonalities in the results reported by the studies (Table 1). In particular, they consistently reported a projected increase in temperature and a geographically variable change in precipitation over the coming decades. High latitude, equatorial and some sub–tropical regions are expected to experience increased precipitation, while mid–latitude and some sub–tropical regions are likely to have decreased precipitation.[2] Smaller increases were projected under the lower emission scenarios.[31,32] Much lower population at risk was projected when the $HadCM_2$ model or previous IS92a scenarios were used compared with the IPCC new version of scenarios.[20,33]

## Projections

The studies reported a range of results and projections regarding future malaria transmission. These results are now summarised.

The major component of the disease burden due to high–fatality malaria is expected to remain located in the highly endemic countries of tropical.[29,31,32,34] Even under the optimistic A1B scenario, which only accounted for GDP per capita increase without taking into account the effects of CC, the disease will still remain in Africa.[29] The population at risk is projected to increase in East and South Africa, with the additional population at risk increasing to approximately 49 million by 2030[32] and 21–67 million by 2080,[31] but decreasing in West Africa.[32,33]

There will be a northward expansion into West Asia and East Asia by 2030, 2050 and up to 2080.[31-33] The highest risks for the expansion of malaria transmission have been found in the non–endemic regions bordering on malarial areas in Africa, South America and South East Asia.[20,29,32,33] Of particular importance is the increase of epidemic potential at higher altitude regions such as the eastern highlands of Africa or the Andes region in South America, where an increase in temperature of several degrees may raise the epidemic potential sufficiently to change normally non–malarial areas to ones with seasonal epidemics.[20,32,34] However, in areas such as Central America, malaria transmission areas are already at the limits of vector distribution and consequently the increase in the population at risk is smaller compared to other regions.[32,34]

In areas of lower endemicity, a small rise in minimum transmission temperature has the potential to lead to a substantial increase in malaria incidence.[25,34] Where malaria is common and there are often high levels of immunity in the population, the change is far less pronounced.[32,34]

## The global trend

The population at risk is projected to be 4.6 billion by 2030 and 5.2 billion by 2050 under A1B scenario relative to the baseline of 1961–1990.[29] There will be up to 400 million additional population at risk by 2080[32,34] although different scenarios were used to make these projections. There will be greater changes in populations at risk for infection by *P. falciparum* than by *P. vivax* due to the higher temperature for development of the former.[34]

Non-climatic factors such as GDP, malaria control status and vector limit can also alter the potential future malaria risk. In 2050, the population at risk was projected to be 5.2 million when only climatic effects were considered, 1.95 million when the combined effects of GDP and climate were taken into account, and 1.74 million when considering GDP effects only.[29] The additional population at risk was projected to decrease from 560 million to 450 million when the absence of the vector was considered to be a limitation for transmission by 2080.[34] The net additional population at risk increases or decreases largely depends on adaptive capacity. In the areas where malaria is restricted by climate factors in specific arid and highland regions, the capacity to develop and sustain malaria control programmes is key to managing any climate-induced increase in malaria. In countries where malaria transmission occurs year round and control capacity is weak, CC may have little impact upon the malaria situation.[31] Climatic factors are more likely to have a substantial effect on malaria transmission in countries whose GDP per capita (GDPpc) is currently less than US$20,000.[29]

# African trend

## Overall view

Six studies focused on the projection of future CC on malaria in Africa, five of which applied the projection under IPCC scenarios.[25–27,35,36] One study projected global malaria distribution using the HadCM$_2$–generated scenarios.[28] The potential for malaria transmission was projected to increase the least under the lowest emission scenarios, and the most for the largest rise in temperature coupled with a moderate reduction in rainfall.[25,27,35] The suitability for malaria transmission has been projected to change by varying degree and direction over much of the Sahel, eastern and southern Africa. Areas in tropical Africa where malaria transmission was projected to become more stable or unstable are often located side by side, which leads to changes in the epidemic potential.[25] The population at risk was projected to decrease across West Africa and the Sahel because of a drier climate,[27,35] but to increase in both east and south Africa.[27,28]

## Next half century trend in Africa

The population at risk was estimated to increase from 638 to 722 (13% of baseline) and 731 (14% of baseline) million by 2015 and 2030, respectively, under the worst emission scenario.[36] The largest changes projected to occur by the 2020s are strong declines in transmission rates in western Madagascar and large parts of southern east–Africa, which encompass northern Zimbabwe, western Mozambique and southeastern Zambia. With the exception of a small southward range expansion into the upland fringes of northern South Africa, highland areas are projected to experience very small increases in transmission through this period under the $HadCM_2$ medium–high scenario.[28] In Sahel, projections for the 2020s and into the 2040s show that the area of potential malaria epidemic risk will shift southwards by about 1–2 °, with the largest increases in West Africa for the Adamawa (around 7 °N, 12 °E) and Jos Plateaus (at about 10 °N, 8 °E) in comparison to levels observed between 1960–2000.[25] Malaria epidemics were projected to become less likely north of about 16 °N, while the frequency of epidemics is expected to increase farther south due to densely distributed population.[25]

Climate is just one of the many factors that have been reported to affect malaria transmission. Other social and ecological factors also play important roles. For example, the impacts of CC on malaria transmission potential are reportedly expected to be reduced by urbanisation, but exacerbated by population growth.[36] The population at risk is expected to increase from 638 to 781 million by 2015, and 1.031 billion by 2030, after taking the population growth into account.[36] When urbanisation is taken into account, these estimates decrease to 758 and 972 million, respectively.[36]

End of the century trend

Up to 2100, a large area of south–central Africa and the western Sahel are projected to no longer be suitable for *falciparum* transmission, with specific areas including the central African Republic, Ethiopia and Guinea.[25,26]. Strong southward expansion of the transmission zone has been projected to continue into South Africa.[25,27,28] West Africa (e.g., Mali, Ghana, and Burkina Faso), Namibia and Mozambique in southern Africa are projected to show a fall in person–months of exposure.[35] In Zimbabwe by 2100, the results of the suitability of malaria transmission varied with the direction and amplitude of projected temperature and precipitation change. The effect of a temperature increase would be greatest on malaria transmission potential at high altitude, while a temperature increase combined with a decrease of precipitation may result in a reduction in transmission across the lower and relatively drier areas.[37–39]

It is generally agreed that CC will increase the spread of malaria in African highland areas. For example, Ermert et al.[25] and Thomas et al.[28] projected an increase in malaria suitability of the East African highlands by 2050. Egbendewe-Mondzozo et al.[26] projected large increases in the number of malaria cases in the highland countries of Rwana, Burundi, Uganda and Tanzania by 2080–2100. These projections suggest that malaria will climb to formerly malaria-free zones above about 2000 m, such as the Western Kenyan highlands.[25,28] However, not all highland areas were projected to become suitable for malaria transmission. For example, projections of the impact of CC on the malaria epidemic risk in Tanzania have shown very little change, even by 2080[28] and at least a 10% decrease in malaria cases will be observed in Ethiopia by 2080–2100.[26]

It is estimated that on average there will be around 3.9 billion person–months (528 million people) of exposure to malaria in Africa every year between 2070 and 2100 compared with the period of 1920–1980.[35] Cost projections indicate that the vast majority of the countries in Africa will see an increase in the costs of treating the disease between 2080 and 2100. Even under the minimal IPCC scenario, some African countries may see their in–patient treatment costs for malaria increase by more than 20% from the 1990–2000 baseline.[26]

## The projections in areas other than Africa

Five studies included in this review projected the impact of CC on malaria within a specific country. These included two studies focusing on Germany.[19,40] and the other three on

India.[30,41,42] An assessment in Germany projected that by 2020 to 2080 the main part of Germany will show a potential of a 3–month transmission window under various scenarios. Some areas allowing malaria transmission during 4 months by 2050 to 2080 are mainly found in Eastern Germany such as Brandenburg and Saxony.[20] The assessments in Lower Saxony, Germany revealed a potential seasonal transmission window of 2 to 6 months from 2020 to 2100 due to higher summer mean temperature increases from May to October.[40] The assessment in India projected an increase in the malaria transmission window in northeastern and western states by 2030,[30] by 2050[41] and the later part of this century.[42] Earlier months for transmission were projected in east coastal districts due in part to increased temperature.[30,41] Garg and his colleagues[42] projected the similar spatial distribution trends in India, and further warned that the mismanagement of canal irrigation systems for malaria control will enhance malaria incidences while high per capita income will reduce the impacts considerably.

## DISCUSSION

Projecting the future spread of malaria under various CC scenarios is essential for policy-makers to identify vulnerable communities and to better manage malaria epidemics. This review found that the impact of CC on the malaria transmission is heterogeneous over space and time. Although many studies in this review projected an increase in population at risk as CC continues,[25,26,29,32,35,39] some studies found conflicting results. For example, at a global level, projections by Rogers and Randolph[33] showed little effect of CC on malaria, with distributions of *P. falciparum* malaria showing remarkably few changes even under the most extreme 2050 climate scenarios. In a review of several projection studies by Gething et al.[43] the endemicity was even found to decline by up to two orders of magnitude by 2050 due to control measures.

The work by Rogers and Randolph has been criticised for using contemporary rather than historical malaria distributions. It has been suggested that this results in bias towards establishing multivariate relationships relatively inert to future CC, as the historical distributions were sampled from the centre of the ancestral malaria distribution.[25] For the study by Gething et al., concerns have been raised regarding the methodology used for interpolating data, as it appears to eliminate the existing temperature–malaria relationship when survey data are sparse. Also, it was suggested that substituting global results will tend to misrepresent changes in malaria prevalence in these regions.[44]

Criticisms have similarly been made about those studies that described a significant increase in CC-associated malaria.[45] These have included concerns about the robustness and accuracy of the results, as well as the potential for conflicting projections, due in part to the complexity of CC impacts on malaria transmission and the projecting framework, the limitation of the available techniques and data, and lack of dynamic knowledge. Some researchers have argued that climate, if associated with malaria resurgence, is not necessarily the ultimate and only cause of such change.[45] Emphasising the abuse of CC evidence or suggestive observations that have been made has been a cliché in the research agenda, which is called to be avoided when it is unsubstantiated.[46]

The interaction of climatic factors and malaria transmission cycles, the complexity and limitations of projection frameworks and the associated uncertainties in future CC and socioecological changes have limited researchers in achieving more accurate and consistent results. We will address these issues in details in the subsequent sections.

## Interaction of climatic factors and malaria transmission cycles

Numerous theories have been developed in recent years to explain the relation between CC and malaria, including increased proliferation and reproduction rates of vector and pathogen at higher temperatures, an extended transmission season, changes in ecological balances, and climate–related migration of vectors, reservoir hosts, or human populations.[11,47] These factors suggest that malaria will become increasingly widespread in the future due to global warming.[3] The main changes are likely to occur in areas with temperate climates where mosquitoes are already abundant and where development of the parasite is currently limited by low temperature, such as in large parts of North America, Europe and Asia.[31–34]

An optimum temperature for increasing transmission potential is found between 20 and 30 °C.[11,19,48] with differences found between regions. Epidemic risk increases with temperature until a maximum threshold is reached. At extremely high temperatures, the accelerated development of the parasite and the increased biting rate can no longer compensate for the decreasing mean life expectancy among the mosquitoes.[34] and the reduced survival of the pathogen of *P. falciparum* when temperatures reach higher than 35 ºC.[49–51] Conversely, there is also a typical threshold below which transmission ceases. Below 16 °C the aquatic stages of tropical anophelines fail to develop or breed, while *P. falciparum* fails to develop between 16 °C and 19 °C[50,51] and the minimum temperature for parasite development of *P. vivex* lies between 14.5 °C and 15 °C.[19,20,40] For example, the upper limit observed for malaria transmission in the African highlands was estimated to be approximately 2000 m. One of the reasons for this limit is that temperature declines as altitude increases.[50]

Changes in rainfall may also alter the quality and availability of mosquito breeding sites.[32,47,52] Rain is related to humidity, which affects the longevity of the adult mosquito.[32,52] An optimum level for rainfall associated with seasonal malaria transmission has been estimated to be an average monthly precipitation of 80 mm, maintained over at least four months (with suitable temperatures).[32,52] Regions where rainfall is the primary limiting factor are especially prone to epidemics with increased rainfall. The catastrophic malaria epidemic in Ethiopia in 1958, for example, was largely associated with unusually high rainfall over a long period of time.[35] The combined effects of both temperature and rainfall exacerbated the epidemic of malaria in northern South Africa, along the southern edge of the Kalahari Desert and into Namibia, where a prolonged malaria season was found to be related to increased temperature and decreased occurrence of frost.[20] Decreased precipitation led to a significant decrease of malaria transmission in regions with stable malaria endemicity like the Sahel,[25] the north of Botswana towards the far north of Mozambique.[28] In the regions where the monthly rainfall exceeds the threshold, the decline in precipitation is beneficial for the growth of the mosquito population. For example, the malaria suitability window was projected to decrease by 2040s in the south of the Sahel, except for areas between Liberia and Ghana due to a reduced flushing of breeding habitats.[25]

## Complexity of a projection framework

### The various global temperature scenarios

The IPCC Special Report on Emissions Scenarios (SRES) accounted for future economic and population growth, two factors which partially contribute of the uncertainties in future GHG emissions. These scenarios are widely used in the development of related government policy and are grouped into four families (A1, A2, B1 and B2), which are projected using the general circulation models (GCMs).[53] These scenarios were used in the IPCC Third Assessment Report.[54] and the IPCC Fourth Assessment Report.[2] Six IS92 scenarios (IS92a to f) had been used in the earlier IPCC Second Assessment Report of 1995.[55] IS92a was widely adopted as a standard scenario for use in impact assessments.[56,57] Business-as-usual and Accelerated policies scenarios were used in the IPCC First Assessment Report of 1990.[58] Generally, the latest scenarios represent the current demographic, social, economic, technological, and environmental developments.[2] The IPCC Fifth Assessment Report, due in

2014, will adopt Representative Concentration Pathways (RCPs) on scenario development process, which will develop global scenarios for two time periods (“near–term” and “long–term”).[59]

The limitation of climate models

GCMs are the most advanced tools currently available for simulating the response of the global climate system to changing atmospheric composition. The most important tool remains the coupled atmosphere ocean general circulation models (AOGCMs). There have been notable improvements on atmospheric, oceanic and cryospheric components including 23 AOGCMs from 18 modelling groups that were widely used.[2] The Hadley Centre for Climate Projection and Research in UK that provide systematic climate modelling procedures with the newest versions of $HadCM_2$ and $HadCM_3$ was mostly used in this review. In the coupled model intercomparison of Table 8.1 in the IPCC Fourth Assessment Report, it is generally seen that different climate variables are simulated with different skills by the different models, such that no model is nearest to the observed climate for all parameters. New model or model concepts could possibly bring additional insight into the complex behaviour of the climate system. For example, Ensembles of models from different modelling centres or using Earth System Models of Intermediate Complexity (EMICs) to simplify representation of some physical processes to save the large computational cost by comprehensive AOGCMs.[2]

However, the grid resolution of GCMs is too coarse (typically a few hundred kilometres in resolution) to capture adequately the effects of local terrain on temperatures and rainfall, and in addition to this, model biases are not corrected due to the direct use of GCMs, and some important uncertainties (e.g., land use) are not included.[25] Furthermore, the accuracy of GCMs in projecting the variation of climatic variables such as precipitation, to which biological systems are very sensitive, is unknown.[33] They are also unable to reliably project changes in the frequency of droughts, a factor that can have significant effect on malaria transmission.[34,54,60]

## The translation of climate models from global to local level

The projection of future malaria risks must take account of local climatic conditions.[25,32,34] Local– and regional–scale studies permit a more detailed analysis of climate–malaria relationships and are likely to be more useful for public health officials than broad, global–scale studies. Specifically, finer–scale analyses facilitate incorporation of local features and characteristics and may provide a greater opportunity for intervention and response, given that public health programs are typically applied at the regional or local level .[35,44]

Moving from large–scale climate projections to smaller more detailed spatial scales requires the application of ‘downscaling’ techniques that bring additional information to bear on the region in question. Downscaling methods fall into two broad categories: dynamical downscaling, using high–resolution, regional climate models, and statistical downscaling, based on statistical relationships between large–scale and regional predictor variables.[61] Various climate models used in the projection studies may produce different climate changes and correspondingly shift the future distribution and variability of malaria transmission. For example, the transmission gate for the periods of 2021–2050 and 2051–2080 calculated by Regional Model (REMO) showed larger areas at risk than those calculated by the Weather condition–based regionalisation method (Wettreg) since REMO projected a more severe temperature rise.[19] To date, no standard regional model for future local climatic projections has been specified. The Coordinated Regional Downscaling Experiment (CORDEX) program was recently established by the World Climate Research Program (WCRP), the aim of which is to develop an international coordinated framework and generate improved regional CC projections worldwide.[62]

Most included studies used coarse spatial resolution of 2.5° latitude by 3.75° longitude. Some studies compared the results from different resolutions. Hay et al.[36] reported that when the resolution of 2.5°×3.75° was replaced with 10'×10', the population at risk increased from 603 million to 722 million by 2015 and from 617 million to 731 million by 2030, respectively based on data of 1961–1990 under the same A2 scenario.[36] Much smaller spatial structures can now be studied in more detail for various highland territories.[25] The higher resolution climate grid is able to describe regions that the model shows as unsuitable for malaria under the observed climate and that become suitable with CC.[32] Therefore, the results might shift when a more advanced technique is applied. However, it is much more computationally difficult and the uncertainty associated with the projections may increase if a finer–scale analysis is used.

## The complexity of modelling future malaria transmission

It has been a complex task to estimate future trends in malaria incidence in that it requires the use of integrated mathematical models based on variables describing climate, vectors, parasites, land–use, social–demography, human population, and other changes.[37,63]

A variety of methods have been proposed for the risk assessment of malaria, though a standard framework is yet to emerge.[64] Better modelling of the basic climate–malaria association and a comprehensive assessment of current and future climate–related burdens of malaria transmission potential are needed.[3] At this stage, the models used to project future transmission of malaria under CC scenarios can be divided roughly into two categories: biological models and empirical models.

Biological models for malaria distribution are usually based on the temperature dependence of mosquito longevity, blood–feeding intervals, and the development period of the malaria parasite within the mosquito. Each of them affects the rate of malaria transmission. These models include a lower temperature limit, below which all development of the malaria parasite ceases, and an upper threshold of mosquito and parasite lethality.[20,43] In addition, the suitability (or unsuitability) of habitats for these vectors, which require a minimum level of atmospheric moisture, is defined by the ratio of rainfall to potential evapotranspiration.[33]

The empirical models often pattern–match contemporary climate measurements to the current malaria range and then apply these same numerical relationships to possible future climates to project the future malaria distribution.[35] These statistical approaches can incorporate interactions between climatic and other factors,[29] but have been criticised by some authors because not only do they often assume that the relationships between climate and malaria will remain unchanged into the future,[35] but they often do not describe the full complexity of malaria transmission.[29] An advantage of statistical over biological approaches is that in situations where biological knowledge is incomplete, uncertainty will thereby increase.[33]

A number of extensions to these models have also been considered. To model the impacts of CC on malaria risk in Africa, a hybrid, statistical–biological model approach was adopted by Thomas et al.[28] This model used fuzzy climate suitability valued between 0 and 1 to define the suitability of local climate to malaria transmission.[35] Recently, Ermert et al.[25] applied a new version of the Liverpool Malaria Model ($LMM_{2010}$), originally formulated by Hoshen and Morse,[65] which improved the understanding of both the ability of weather forecasts to predict weather and of biological models to predict disease. This was argued to present a path to the understanding of probabilistic solutions to non-linear epidemic prediction problems.[65] However, there is no consensus on how to use these modelling techniques. An important, but as yet unsolved problem is how to disentangle the effects of CC on malaria transmission from model uncertainties due to such issues as different climate sources being used for the baseline,[35] projections into the future,[35] various emission scenarios,[19] the interpolation process,[35] and different regional climate models.[19,38]

## Uncertainties of the whole projection procedures

### Uncertainty in climate change and its impacts on malaria

A projection of climate changes is certain in some areas but uncertain in other areas. For example, in West Africa, rainfall projections are not possible. About one third of the GCMs reveal lower precipitation values; a third predicts higher precipitation values; and the remaining third show a mixed rainfall picture.[2,66] The timing and pattern of rainfall in long term is not projected even by state of the art models.[42]

The combination of temperature and rainfall are crucial for parasite development in that higher temperatures accelerate the larva development and need less months of rainfall to reach a malaria transmission level.[52] The projected results (e.g., transmission window or transmission potential) are determined by the suitability for malaria parasite to grow.[25,35,42] Future CC may alter the adaptation of the mosquito development speed and alternatively change the dynamic period to be suitable for transmission. For example, the population at risk in Latin America by 2080 has been projected to decrease by 198 million under the A1FI scenario versus 298 million under the A2 scenario with the disparity in projections due to choosing the limit for average monthly precipitation of 80 mm compared with assessing the effects of temperature only.[32]

Finally, the degree and distribution of malaria will vary when output criteria changed such as the time periods of the transmission window. The vast majority of additional population at risk occurs in the areas where the potential transmission season has increased from 0 to 1 or 2 months per year. The global estimates are reduced if transmission risk for more than 3 consecutive months per year is considered. A net reduction in the global population at risk is projected under the A2 and B1 scenarios.[32]

Uncertainty in socioecological changes

The distribution of malaria under the CC scenarios should be determined by integrated consideration of both climatic and non–climatic factors. Climate is only one of many factors influencing malaria distribution and the projection of malaria based on climatic conditions alone may not present a complete picture.[11] Drivers known to influence populations at risk of malaria are CC, demography and urbanization.[35,67] Investigations of the roles of other potential factors in malaria transmission have also been suggested as areas for further research such as changes in land use, socioeconomic changes and increased air travel.[29,68,69] Other potential impacts such as HIV/AIDs epidemics, interventions/control programs, nutrition, and poly–parasitism changes have been discussed qualitatively and are not considered further here.[35]

High rates of population growth in malarious areas already ensure an increase in the population at risk.[20] The United Nations Population Division on the World Population Prospects (UNPD_WPP) has provided population scenario data at a national level and inter–censual growth rates by five–year period, allowing population estimates to be projected on a country by county basis.[38] However, uncertainties in growth rates mean that, such projected population estimates are subject to debate.[70–72] Population scenarios vary greatly, and the population grids do not take into account urbanisation or coastal migration.[32]

The urban and rural status of a population can be inferred from its associated population density.[29] Malaria has been considered a predominantly rural disease in Africa, primarily because suitable vector breeding sites are scarce in highly populated areas.[73] The urban conditions make life less suitable for mosquito vectors (e.g., less abundant and more polluted breeding sites) and easier for humans to protect themselves from the disease (e.g., improved socioeconomic status, housing quality and physical access to preventive and curative measures).[38] There have been few attempts to project the impact of urbanization on the future population at risk of malaria.[35] Much of what we know about malaria transmission in rural environments might not be applicable in the urban context.[74]

Human induced land cover changes, such as changes in forest, agriculture, irrigation, dams and desertification are likely to influence the trend of CC especially at time scales of several decades into the future. For example, it has been argued that land use changes have accelerated precipitation decline by nearly three decades over west Africa.[75] Deforestation, along with associated land use changes and human resettlement, has contributed to changes in malaria and its vectors throughout the tropics. The expansion of malaria is also occurring in Amazonia, where deforestation has been shown to provide suitable breeding sites for *Anopheles darlingi*, with deforested breeding sites yielding over a hundredfold increase in biting rates, even after controlling for human population density.[76] However, both land use and land cover changes are largely not included in state–of–the art climate models.[25]

It is plausible that GDPpc can be used as a proxy for preventative measures such as screened windows, insecticide treated nets or therapeutic measures.[29,69] The number of population at risk in 2050 was projected to decrease from 5.2 billion to 1.95 billion when GDPpc was considered in projections by Béguin et al.[29] However, the dynamics of socioeconomic systems are governed by highly complex processes that are not well understood, and socioeconomic development can be influenced to a large degree by unanticipated factors like the recent financial crisis.[29]

Imported malaria cases are increasingly reported in many countries of the world as the number of people travelling overseas continues to rise, with a disproportionate increase in visits to tropical areas where malaria transmission is active.[68] Approximately 25–30 million international travellers from non–tropical regions visit countries where malaria is endemic annually, with approximately 30,000 cases of travel–related malaria acquired.[68] Limited evidence suggests that a detailed itinerary is necessary to assess risk of air travel on malaria including purpose (e.g., visiting friends or relatives), regions, times of the year, the time spent in the endemic area and activities undertaken. For example, camping in a jungle for three weeks poses a much higher risk than a three day visit to an urban area with air conditioned accommodation.[77] The GeoSentinel is a global sentinel surveillance network that was established in 1995 by the International Society for Travel Medicine and the Centres for Disease Control for the surveillance of travel related morbidity. However, individuals in the GeoSentinel database are not representative of all international travellers and few studies have provided representative indicators of imported malaria in travellers' risk of malaria acquisition.[78] Therefore, there is limited evidence on which to base traveller information in the projection modelling for future CC impacts on malaria. However, it remains important to integrate the association between importation, passenger numbers, and travel source into models if sufficient data exist.

## Challenges and research needs

Future risk assessments of CC will ultimately need to integrate global climate–based analysis with local socioeconomic and environmental factors, in order to guide comprehensive and sustainable preventive strategies to control and prevent malaria transmission.

Firstly, a better understanding of the direct and indirect effects of climate variability on malaria cycles is required for the projection of potential impacts of CC on malaria.

Secondly, the methodology for projecting future CC–related malaria risk needs to be improved. Projection models on CC and malaria need to be developed not only at a global scale but also at regional and local levels. This is an area which is of relevance not only for developing adaptation strategies to the direct CC effects on malaria but also for planning interventions to reduce the effects of major confounders such as land–use and ecological degradation.

Thirdly, a standard procedure or framework for modelling is necessary. In particular, the development of combining process–based models (capturing the biology of the malaria system) with a statistical approach is needed.[61] Multi-malaria model projections that are based on multi GCM or RCM data will be state–of–the–art in the near future since individual models can exhibit significant biases in some sub-regions and seasons. Several baseline conditions may need to be selected to represent a range of historical climatic conditions.[79] The IPCC Fifth Assessment Report will provide a prospective integrated pathway for future scenario analysis both from providing more consistent and regional scenarios, and disentangling the CC projection, socio–economic projection and vulnerability/adaptation projection which are able to combine local conditions in future projection research.[59]

Fourthly, more data on social and biological factors are required to validate and to improve the malaria models. For example, entomological and parasitological continuous observations are needed (e.g. for ten years and more) and malaria control activities need to be incorporated in the model. Such data are, for example, required for seasonal malaria projection. It is also important to consider the atmospheric changes that were responsible for the presented malaria projections.

It is also important to include uncertainty in the derived projections and anticipated impacts. This is critical for informed analysis and policy determination. A critical concomitant issue will be the effective communication of these uncertainties and education on their interpretation.

Finally, a key challenge is to improve surveillance and primary health information systems in low resource regions and communities, and to share the knowledge and develop adaptation strategies across different sectors, communities, and societies.

## Public health implications of future projections of CC impacts

Projections of future CC impacts may have the following public health implications:

First, appropriate projections of malaria risks would provide decision–makers with the opportunity to proactively initiate activities to identify vulnerable communities and to develop effective strategies to control and prevent malaria outbreaks. The following key knowledge gaps have been identified in this area: a lack of region–specific projections of changes in health–related exposures and a lack of research on health outcomes concerning various future emissions and adaptation scenarios, particularly in developing countries.[3] Advances in projection methodologies are generating new opportunities to minimize the impact of CC on health.[80] For this reason, using climatic indices along with projecting models can alert authorities of possible changes in the risk level, either immediately or in the near future.[9,81]

Second, malaria early warning systems (MEWS) are a win–win strategy that reduces the risk of malaria epidemics whilst increasing adaptive capacity that is essential, especially for developing countries.[3] The ability to project an outbreak months or years in advance based upon climatic indicators may make it possible to implement early intervention initiatives or aggressive vector control programs and guide the vulnerable populations away from trouble spots.[47]

Third, assessing the risk of malaria transmission potential will alert policy makers to the health, economic and political consequences of malaria epidemics. This will increase the potential to reaching agreements for international collaboration and/or close cross–sectoral cooperation at regional or local levels.

Finally, these projections may encourage a new advocacy and public health movement that is needed urgently to bring together governments, international agencies, non–governmental organisations (NGOs), communities, and academics from all disciplines to scale up malaria control efforts at a global level.

## CONCLUSIONS

The projected effects of CC on the risk of malaria transmission potential are mixed and heterogeneous over the space and time, although most studies agree on the increase of highland malaria. Improvements in knowledge regarding the dynamic affects of climate on the malaria transmission cycles, advancement in modelling techniques and incorporation of uncertainties in future socioecological changes are critical factors to enhance our ability for projecting the impact of future CC on malaria transmission.

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**Table 1. Characteristics of studies on projecting malaria transmission under climate change scenarios.**

| Reference | Setting | Projected period | Output variables | Projection results |
|---|---|---|---|---|
| **IPCC scenarios** | | | | |
| Béguin et al., 2011[29] | Global level | 2020<br>2050 | Population at risk | In 2030 and 2050, the projected population at risk is approximately 4.6 and 5.2 billion when considering climatic effects only, 3.58 and 1.95 billion when considering the combined effects of Gross Domestic Product (GDP) and climate, and 3.52 and 1.74 billion when considering GDP effects only, respectively. |
| Ebi et al. 2008[31] | Global level | 2030 | Population at risk<br>malaria cases, the cost of interventions for malaria | Under the worst scenario, climate change is projected to increase the numbers of malaria cases by 5%. The largest increases are projected to be in Africa and Southeast Asia. The total costs under the three scenarios were estimated $1573 to $8781 by 2030. Total investment needs in 2030 for combating malaria would be $36 to $ 50 billion. |
| Van Lieshout et al 2004[32] | Global level | 2080s | Additional population at risk | The greatest additional populations at risk are in East Africa, Southern Africa, Pakistan, Afghanistan and China by 2080. These locations vary between climate scenarios although most scenarios indicate reduced transmission in tropical South America, Central America, Pakistan, north-west India, and around desert regions. Net reductions in the population at risk are primarily attributable to decreases in precipitation in the climate scenarios. The population at risk reduces or increases for countries with good and poor capacity to control the disease. |
| Martens 1995[34] | Global level | 2100 | Malaria incidence and disease burden | Due to temperature increases by the year 2100, the potential for malaria transmission would exist in large parts of temperate climates in North America, Europe and Asia and the epidemic potential will increase at higher altitudes within malarial areas such as the eastern highlands of Africa or the Andes region in South America, irrespective of scenarios. |
| **Non-IPCC scenarios** | | | | |
| Rogers and Randolph 2000[33] | Global level | 2050 | Additional population at risk | Only a small extension is projected to be northward into the southern United States and Turkey, Turkmenistan, and Uzbekistan, southward in Brazil and westward in China by 2050 under high scenario. Other areas are projected to diminish. The additional population at risk will be 23 million under the medium-high scenario and 25 million under the high scenario. |
| Martens et al. 1999[20] | Global level | 2020<br>2050<br>2080 | Potential transmission of malaria, population at risk | The magnitudes of the estimated changes in transmission potential depend on the climate scenario and specific characteristics of the malaria vector concerned. The numbers of additional population at risk of malaria in 2080 due to CC is estimated to be 300 and 150 million for *P. falciparum* and *P. vivax* types of malaria, respectively, under the HadCM3 CC scenario. Under the HadCM2 ensemble projections, estimates of additional people–at–risk in 2080 range from 260 to 320 million for *P. falciparum* and from 100 to 200 million for *P. vivax*. |
| **IPCC scenarios** | | | | |
| Ermert et al. 2012[25] | Sub-Saharan Africa | 2020s<br>2040s | The entomological inoculation rate<br>Year-to-year variability of parasite ratios for children<15 years of age | A decrease spread of malaria over most parts of tropical Africa is projected due to increased temperature and significant reduction in annual rainfall. The intensity of malaria transmission in most of East Africa has a small or moderate increase due to significantly higher temperatures and slightly higher rainfall. Southern part of the Sahel increases due to the beneficial of reduction in precipitation. Highland areas will become epidemic except lower altitude regions of the East African highlands epidemic risk will decrease. |

**Table 1 Characteristics of studies on projecting malaria transmission under climate change scenarios (Continued).**

| Reference | Setting | Projected period | Output variables | Projection results |
|---|---|---|---|---|
| **IPCC scenarios** | | | | |
| Egbendewe–Mondzozo et al. 2011[26] | Africa | 2080–2100 | Cases per 1000 people<br>Treatment costs per 1000 people | Under all scenarios, the equator countries show an increase in number of cases except Central African Republic, Ethiopia and Guinea. The majority of the countries will have an increase treatment costs, particularly the inpatient costs in 2080-2100. |
| Peterson 2009[27] | Africa | 2060s | Population exposed to the vectors | A reduction of 11.3–30.2% of populations living in areas climatically suitable for vector species in coming decades, but reductions and increases are focused in different regions: malaria vector suitability is likely to decrease in West Africa, but increase in eastern and southern Africa. |
| Hay et al. 2006[36] | Africa | 2005<br>2015<br>2030 | Population at risk | People at risk will increase from approximately 0.63 billion in 2005, to 0.87 billion in 2015 and 1.15 billion in 2030 when population growth and urbanisation were taken into account using finer spatial resolution. |
| Tanser et al. 2003[35] | South Africa | 2020s<br>2050s<br>2080s | Person-months of risk | Due to the increase in the length of transmission season, the projected scenarios would estimate a 5–7% potential increase in malaria distribution with little increase in the latitudinal extents of the disease by 2100. Of the overall potential increase of 16–28% in person–months of exposure, a large proportion will be seen in areas of existing transmission. The B1 scenario shows the least increased because of reductions in rainfall and smallest rises in mean temperature; A2a shows the highest increases during the 2020s and 2050s because of the combined effect of slight increase in rainfall and large rise in temperature. The A1FI shows the highest increase by 2100, due to the largest rise in temperature coupled with a moderate reduction in rainfall. |
| **Non-IPCC scenarios** | | | | |
| Thomas et al. 2004[28] | Africa | 2020s<br>2050s<br>2080s | Minimum season length | In the next 30–40 years, the effects of climate change on stable *falciparum* malaria zones in Africa are probably complex and spatially heterogeneous, and that range contractions are more likely than expansions. |
| Ebi et al. 2005[39] | Zimbabwe, Africa | 2100 | Population at risk | Distribution of malaria in Zimbabwe, previously unsuitable areas of dense human population become suitable for transmission. Among all scenarios, the highlands become more suitable for transmission, while the lowveld and areas currently limited by precipitation show varying degrees of change. |
| Hartman et al. 2002[38] | Zimbabwe, Africa | 2100 | Fuzzy logic climate suitability | The net change of climate suitability for stable malaria transmission varied from -37% to 56% under different scenarios. For any scenario, the highlands become more suitable for transmission due to high population density, while the lowveld areas become slightly less suitable. |
| Lindsay and Martens 1998[37] | Zimbabwe, Africa | 2020s<br>2050s<br>2080s | Monthly mean temperature | The effect of a temperature increase would be greatest on malaria transmission potential at high altitudes. In the relatively drier lower altitudes, a temperature increase of 2 °C combined with a 20% decrease of precipitation may result in areas becoming too dry for malaria transmission to make place and in a shortening of the transmission season. |

**Table 1 Characteristics of studies on projecting malaria transmission under climate change scenarios (Continued).**

| Reference | Setting | Projected period | Output variables | Projection results |
|---|---|---|---|---|
| **IPCC scenarios** | | | | |
| Holy et al. 2011[19] | Germany | 2021–2050<br>2051–2080 | Seasonal transmission gate | Both modelling approaches resulted in prolonged seasonal transmission gates in the future, enabling malaria transmissions up to 6 months in the climate reference period 2051–2080. |
| **Non-IPCC scenarios** | | | | |
| Schröder and Schmidt 2008[40] | Lower Saxony, Germany | 2020<br>2060<br>2100 | Seasonal transmission gate | The seasonal transmission gate of 2 to 6 months from 2020 to 2100 due to higher summer mean temperature increase from May to October. |
| **IPCC scenarios** | | | | |
| Dhiman et al. 2011[30] | India | 2030 | Transmission window | Intensity of transmission is projected to increase from 7-9 months to 10-12 months in the Northeastern states, whereas in the east coastal districts, reduction in transmission months is likely due to increased temperature. The Western Ghats is projected to have minimum affects. |
| Garg et al. 2009[42] | India | 2020<br>2050<br>2080 | Transmission window | In later parts of this century, malaria transmission window will increase 10% more states open for all the 12 months. But the southern states will shorten by 2-3 months due to climate change alone. The mismanagement of canal irrigation systems for malaria control enhances the malaria incidences while high per capita income reduces the impacts considerably. |
| Bhattacharya et al. 2006[41] | India | 2050s | Transmission window | Orissa and West Bengal and the southern parts of Assam will still remain malicious under the changed climate conditions. However, central states of Madhya Pradesh, Chhattisgarh and Jharkhand will no longer remain endemic to malaria. Areas like the coastal states of Maharashtra, Karnataka and Kerala in the south, hilly areas like Himachal Pradesh in the North and the Arunachal Pradesh, Nagaland, Manipur and Mizoram in the northeast emerge as regions where transmission windows for malaria will open up. Climate change is likely to increase the transmission windows during winter months in northern India due to increase in lower limit of required conditions. The states like West Bengal and Orissa may experience reduction in transmission windows due to increase in upper limit of temperature. |

**Table 2. Methodological issues of studies on projecting malaria transmission under climate change scenarios.**

| Reference | Baseline time period | GHGs emission scenario# | Temperature exposure | Time resolution | Considered other factors | Model type | Climate projection model | Horizontal resolution |
|---|---|---|---|---|---|---|---|---|
| **Global level** | | | | | | | | |
| Béguin et al., 2011[29] | 1961–1990 | A1B | Mean temperature, mean precipitation, mean temperature of the coldest and warmest month, mean precipitation of the wettest and driest month | Yearly | GDPpcs and population growth | Empirical model: logistic regression model | GCMs: BCM2, EGMAM IPCM4 | 1° ×1° |
| Ebi et al. 2008[31] | 2000 | IS92a, stabilisation at 550 and 750 ppm $CO_2$ equivalent | Mean temperature | Yearly | Socioeconomic development was assumed to not affect the incidence of malaria | Empirical model: MARA/ARMA | GCMs: HadCM2 | 2.5° ×3.75° |
| van Lieshout et al 2004[32] | 1961–1990 | A1FI, A2a, A2b, A2c, B1, B2a, B2b | Mean temperature, Precipitation | Monthly | Current malaria control status classified by expert judgement, population growth | Biological model: MIASMA model | GCMs: HadCM3 | 0.5° ×0.5° |
| Martens 1995[34] | 1951–1980 | BaU and AP | Mean temperature, Rainfall, precipitation, humidity | Seasonal | Population | Biological model | GCM: UKMO | 5° ×7.5° |
| Rogers and Randolph 2000[33] | 1960-1990 | IS92a, Medium–high scenario and high scenario | mean, minimum and maximum temperatures, rainfall, precipitation, saturation vapor pressure, | Yearly | population, travel and trading activities | Empirical model: Maximum likelihood methods | GCM: HadCM2 | 2.5° ×3.75° |
| Martens et al. 1999[20] | 1961–1990 | HadCM2GGa1–4 and HadCM3GGa1 | Mean temperature, precipitation | Monthly | Population, vector limit | Biological model: MIASMA model | GCMs:HadCM2 HadCM3 | 2.5° ×3.75° |
| **Africa** | | | | | | | | |
| Ermert et al. 2012[25] | 1960–2000 | A1B, B1 | Mean temperature, rainfall | Daily | Future land use changes | Biological model: the *plasmodium falciparum* infection model and the Liverpool malaria model | RCMs: REMO | 0.5° ×0.5° |

AP: accelerated policies scenario; BaU: business–as–usual scenario; BCM: The Bergen Climate Model; EGMAM: the ECHO–G Middle Atmosphere Model; GCM: General circulation models; GDPpc: GDP per capita; HadCM2GGa1–4: four greenhouse–gas–only $HadCM_2$ simulations; HadCM3GGa1: greenhouse–gas–only HadCM3 simulation; HadRM2: Hadley Centre Regional Model 2IPCM: an Earth System Model produced by Institute Pasteur Simon Laplace; MARA/ARMA: Mapping Malaria Risk in Africa; MIASMA: Modelling framework for the health Impact ASsessment of Man–induced Atmospheric changes; RCMs: Regional climate model; REMO: Regional Model; UKMO: United Kingdom Meteorological Office.

**Table 2. Methodological issues of studies on projecting malaria transmission under climate change scenarios (Continued).**

| Reference | Baseline time period | Climate change scenario# | Climate exposure | Time resolution | Considered other factors | Model type | Climate projection model | Horizontal resolution |
|---|---|---|---|---|---|---|---|---|
| **Africa** | | | | | | | | |
| Egbendewe–Mondzozo et al. 2011[26] | 1990–2000 | A1B | Temperatures, precipitation, precipitation standard deviation | Monthly | GDP, population, gini inequality index, population density, per capita expenditures, the number of hospital beds per year | Empirical model: Semi–parametric kerbel methods | - | 2.5° ×3.75° |
| Peterson 2009[27] | Not mentioned | A2, B2 | Mean , maximum and minimum temperatures, precipitation | monthly | Population | Ecological niche models | GCMs: HadCM3 CGCM1 | 30×30 km |
| Hay et al. 2006[36] | 2000-2010,<br><br>1961–1990 | Medium–high A2 emission scenario,<br>Averaged A2a, A2b and A2c | Mean and minimum temperatures, total precipitation | Eleven year average | Population growth, urbanization | Empirical model: Bayesian statistical framework | GCMs: HadCM3 | 2.5°×3.75°<br>10'×10' |
| Tanser et al. 2003[35] | 1920–1980 | B1, A2a, and A1FI | Rainfall | 3–month moving average | month interruption in transmission, location and size of major towns, transport infrastructures and uninhabited areas | Empirical model: parasite survey validated model | GCMs: HadCM3 | 2.5° ×3.75° |
| Thomas et al. 2004[28] | 1961–1990 | Medium–high scenario | Mean and minimum temperatures, precipitation, Mean daily minimum temperature of the coldest month | Monthly | - | Empirical model: MARA/ARMA | GCMs: HadCM2 | 0.5° ×0.5° |
| **Zimbabwe** | | | | | | | | |
| Lindsay and Martens 1998[37] | 1931–1960 | Three scenarios: an increase of 2°C, an increase of 2°C with a 20% increase in precipitation; and an increase of 2°C with a 20% decrease in precipitation | Mean temperature precipitation | Monthly | - | Biological model | - | 0.5° ×0.5° |

CGCM: Canadian Centre model; GCM: General circulation models ; GDP: Gross Domestic Product; HadCM: The Hadley Centre model; MARA/ARMA: Mapping Malaria Risk in Africa.

**Table 2 Methodological issues of studies on projecting malaria transmission under climate change scenarios (Continued).**

| Reference | Baseline time period | Climate change scenario# | Climate exposure | Time resolution | Considered other factors | Projecting disease transmission model | Climate projection model | Horizontal resolution |
|---|---|---|---|---|---|---|---|---|
| **Zimbabwe** | | | | | | | | |
| Ebi et al. 2005[39] | 1920–1980 | 350 ppmv-1.4 °C, 350 ppmv-4.5°C, 750ppmv-1.4; °C 750ppmv-4.5°C | Mean temperature, precipitation | Yearly | - | Empirical model: MARA/ARMA | GCMs: CCC, UKMO, GISS and HEND | 0. 05° ×0.05° Intertemporal scaling procedure |
| Hartman et al. 2002[38] | 1920–1980 | 350 ppmv-1.4 °C, 350 ppmv-4.5°C, 750ppmv-1.4; °C 750ppmv-4.5°C | Mean temperature, the mean range between minimum and maximum temperatures, total precipitation | Monthly | - | Empirical model: MARA/ARMA | GCMs: CCC, UKMO, GISS and HEND | 2.5° ×3.75° |
| **Saxony, Germany** | | | | | | | | |
| Holy et al. 2011[19] | 1961–2007 | A1B and B1 | Mean temperature | Monthly | Not reported | Biological model | RCMs: REMO and WettReg, | 12×12 km |
| Schröder and Schmidt 2008[40] | 1947–2004 | Six scenarios: 2020: temperature increase 0.3°C and 0.9°C; 2060: temperature increase 0.9°C and 3.3°C; 2100: temperature increase 1.4°C and 5.8°C. | Mean temperature | Monthly | Not reported | Biological model | - | 2.5° ×3.75° |
| **India** | | | | | | | | |
| Dhiman et al. 2011[30] | 1961–1990 | A1B | Temperature, relative humidity | Monthly | - | - | RCMs: PRECIS | 0.44° ×0.44° |
| Garg et al. 2009[42] | 1998–2000 | IS92a, A2 and B2 | Mean temperature, rainfall, relative humidity and combination of temperature | Monthly | Per capita income, the management of canal systems for malaria prevention | Empirical model: The impact matrix frame work | HadCM2 | 2.5° ×3.75° |
| Bhattacharya et al. 2006[41] | | IS92a | Temperature, relative humidity | Daily | - | - | RCMs: HadRM2 | 2.5° ×3.75° |

CCC: the Canadian Centre for Climate Research; GCM: General circulation models; GISS: Goddard Institute for Space Studies; HadCM: The Hadley Centre model; HEND: the Henderson–Sellers model using the CCM1 at NCAR; MARA/ARMA: Mapping Malaria Risk in Africa; PRECIS: Providing Regional Climates for Impacts Studies; RCM: Regional Climate Model; REMO: Regional Model, Max Planck Institute for Meteorology, Germany, which is based on global ECHAM; UKMO: United Kingdom Meteorological Office; WettReg: Weather condition–based regionalisation method, Climate& Environment Consulting Potsdam, which is based on global ECHAM.

**Figure 1. Procedure of literature search.**